AD-A124 191 POWER CONDITIONING SUBSYSTEM DESIGN(U) RAYTHEON CO BEDFORD MA MISSILE SYSTEMS DIV J J MORIARTY ET AL. NOV 82 BR-13539 AFWAL-TR-82-2108 F33615-79-C-2079 1/1

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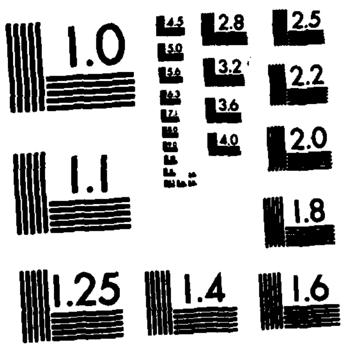

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AFWAL-TR-82-2108

POWER CONDITIONING SUBSYSTEM DESIGN

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Raytheon Company
Missile Systems Division
Bedford, Massachusetts 01730

November 1982

Final Report for Period 17 September 1979 - 31 August 1982

Approved for public release; distribution unlimited.

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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NOTICE

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: AFWAL-TR-82-2108
2. GOVT ACCESSION NO.: AD-A124191
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): POWER CONDITIONING SUBSYSTEM DESIGN
5. TYPE OF REPORT & PERIOD COVERED: FINAL SEP 79 - AUG 82
6. PERFORMING ORG. REPORT NUMBER: BR-13539
7. AUTHOR(s): J. J. Moriarty, P. A. Corbiere, S. Casazza
8. CONTRACT OR GRANT NUMBER(s): F33615-79-C-2079
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Raytheon Company, Missile Systems Division, Bedford Laboratories, Bedford, Mass. 01730
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62203F; 3145-32-54
11. CONTROLLING OFFICE NAME AND ADDRESS: Aero Propulsion Laboratory (POOS), Air Force Wright Aeronautical Lab., AFSC, WPAFB, OH 45433
12. REPORT DATE: November 82
13. NUMBER OF PAGES: 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Power Conditioning
Pulsed Power
Rectifiers
Inverters
Pulse Forming Networks

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This final report describes the results of a 3-phase program to provide designs of lightweight, low volume power conditioning subsystems in the range of 500 kilowatts (kW) to 30 megawatts (MW) as part of the Air Force exploratory development program in high power airborne electrical power supply technology. These designs are based on presently available component technology such as solid-state switching devices, newly developed thyratrons and high energy density capacitors. Although these subsystems are to be

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) operated in a burst mode, active cooling concepts have been utilized wherever they would result in an advantage in weight or volume.

Preliminary designs and approaches were determined for each of the subsystems in Phase I. In addition, those component parameters were identified which appeared to be critical in achieving minimum weights and volumes.

In Phase II detailed designs resulting in weight, volume, cooling requirements, and efficiencies have been determined for a selected group of operating points for each subsystem. The total number of operating points for all four subsystems is 296. The actual number of designs completed was less because of insurmountable limitations in SCRs for the inverter application.

In Phase III four design points were considered for spaceborne applications. Burst-mode duty was maintained for the three-phase rectifier designs, but continuous operation has been assumed for the 500-kW inverter and inverter-fed rectifier design points. This report deals primarily with the Phase III effort.

FOREWORD

This final report was submitted by Raytheon Company, Missile Systems Division, Bedford Laboratories, Bedford, Massachusetts 01730, under Contract F33615-79-C-2079. The effort was sponsored by the Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright Patterson AFB, Ohio 45433 under Project 3145-32-54. Capt. Fred Brockhurst was the Project Engineer at the beginning of the project. Capt. Jerry Clark is currently the Project Engineer. The time period covered by the report is 17 September 1979 through 31 August 1982.

The detailed designs of Phase II were performed primarily by John Moriarty (Principal Investigator), Alvin Herling, John Kelleher and Donald Shute. Preliminary designs of Phase I were prepared by Gordon Simcox, David Donovan and Donald Bingley. Preliminary and detailed designs of unique magnetic components were performed by Paul Corbiere. These efforts have been reported in detail in the interim report for the period 19 September 1979 through 30 November 1981 which was published as AFWAL-TR-82-2005 dated January 1982.

This report describes primarily the extension of certain Phase II designs for spaceborne application which was carried out as the Phase III effort by Stanley Casazza, Paul Corbiere and John Moriarty.

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INTRODUCTION

This final report describes the results of a three-phase program to provide designs of lightweight, low volume power conditioning subsystems in the range of 500 kW to 30 MW as part of the Air Force exploratory development program in high power airborne electrical power supply technology. These designs are based on presently available component technology such as solid-state switching devices, newly developed thyratrons and high energy density capacitors.

Although the subsystems considered in the first two phases were to be operated in a burst mode, active cooling concepts were utilized wherever they would result in an advantage in weight or volume. Burst duration, duty cycle and environmental requirements were modified wherever possible to minimize weights and volumes.

Preliminary designs and approaches were determined for each of the subsystems in Phase I. In addition, those component parameters were identified which appeared to be critical in achieving minimum weights and volumes.

In Phase II detailed designs resulting in weight, volume, cooling requirements and efficiencies were determined for a selected group of operating points for each subsystem. The total number of operating points for all four subsystems was 296. Since each point required a separate design for minimum weight and minimum volume, a total of 592 point designs were undertaken. The actual number of designs completed was less because of insurmountable limitations in SCRs for the inverter application.

In Phase III four design points were considered with respect to spaceborne applications. Burst-mode duty was maintained for the three-phase rectifier designs, but continuous operation was assumed for the 500-kW inverter and inverter-fed rectifier design points. This report deals primarily with the Phase III effort since the first two phases have already been described in detail in the interim report (Reference (1)) which was published earlier this year.

A summary of the subsystem specification ranges is shown in Figure 1 in the form of a block diagram for a typical system which could be composed of the subsystems under study. Only those subsystems shown below the dashed line in the figure are considered in this study. Furthermore, interfacing components between subsystems have not been

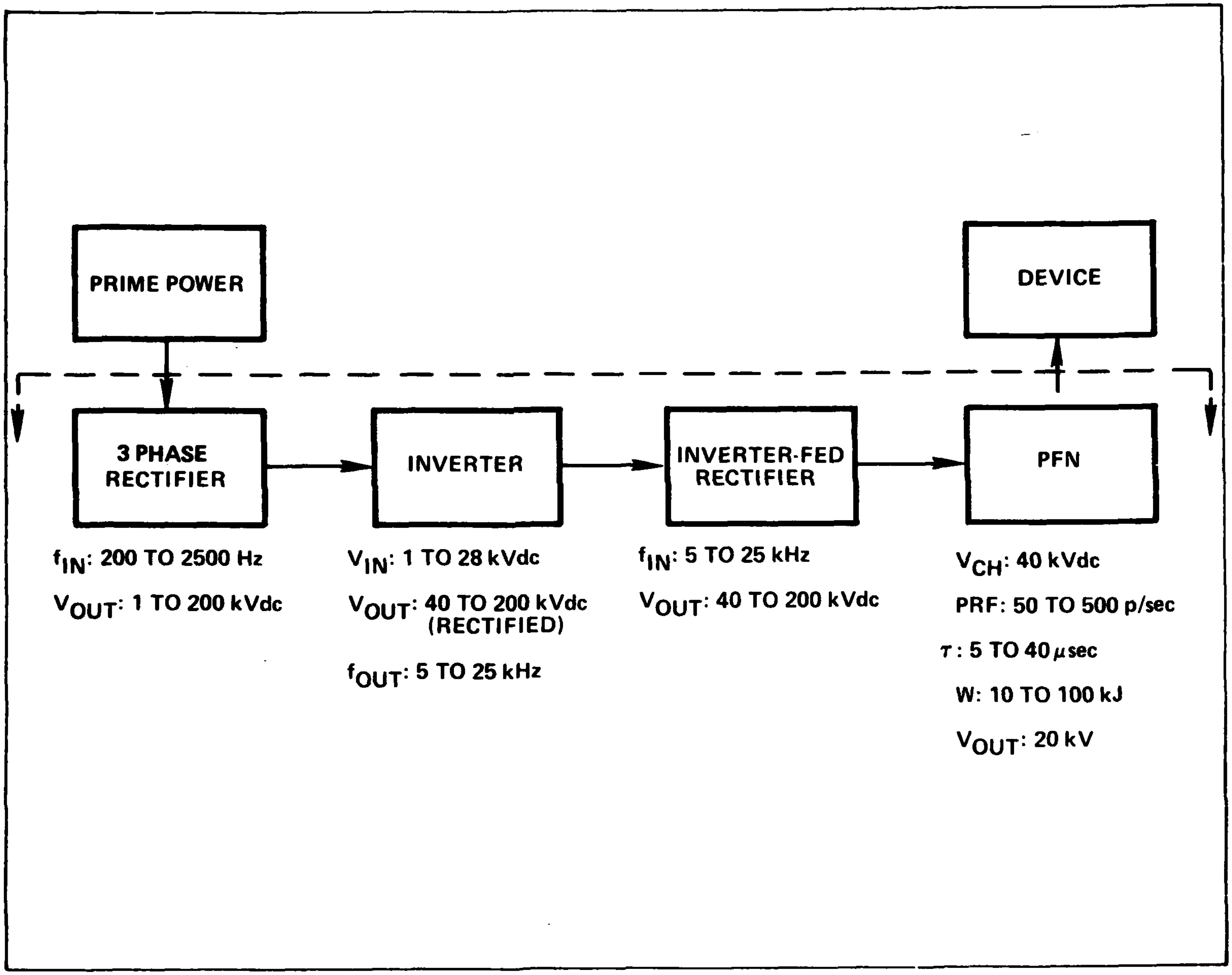

Figure 1 - General Subsystem Specifications

included, since such components would vary considerably with the overall system packaging and insulation approaches. It should be understood that many complete systems could be conceived which would not include all four subsystems shown in the block diagram.

The environmental and operational limitations used in Phase I are summarized below:

- Ambient air and water temperature: 20°C
- Active cooling media: circulating air and water
- Altitude: sea level to 10,000 ft
- Burst duration: 5 min
- Operating life: 100 hr

In an effort to reduce the subsystem size and weight, these restrictions were modified in Phase II as follows:

- Ambient air and fluid temperature: 20°C
- Active cooling media: air, oil and water
- Altitude: sea level to 10,000 ft
- Burst duration: 2 min
- Operating life: 100 hr

These conditions were again modified considerably for Phase III:

- Spacecraft wall temperature: 20°C
- Cooling: conduction to space radiators
- Altitude: earth orbit of 1000 km
- Burst duration:

  1) 2 min each 24 hr for three-phase rectifier
  2) continuous for the inverter and inverter-fed rectifier

- Operating life: 5 yr

A brief summary of the results of the first two phases is given in the next section, and the results of the Phase III effort are presented in subsequent sections.

SECTION II
PHASES I AND II DESIGNS

The purpose of Phase I was to develop design concepts for the four subsystems and to test these concepts by preparing preliminary designs in both minimum weight and minimum volume configurations at six design points within the range of interest for each subsystem. In addition, this preliminary design effort was required to determine those device parameters which would have a critical effect on subsystem weight or volume.

The results of this effort were presented to Air Force and device manufacturer audiences on the 12th and 26th of February 1982, and were summarized in Reference 1.

Using the concepts developed in Phase I the detailed designs for each of the four subsystems were developed in Phase II. These results, which were presented in the Air Force on 22 January 1982, are summarized in Tables 1 through 4.

Further details as well as schematics and artist concepts of several of the designs can be found in Reference 1.

TABLE 1
THREE-PHASE RECTIFIER DESIGNS

					Minimum Weight									Minimum Volume		
Average Power MW	Input Fre-quency Hz	Output Volt-age kV	Heat Load kW	Eff. %	Dry Weight lb	Wet Weight lb	Volume ft^3	Air Flow CFM	ΔT Air C^o	ΔP Air in-H_2O	H_2O Flow GPM	ΔT H_2O C^o	ΔP H_2O psi	Dry Weight lb	Wet Weight lb	Vol-ume ft^3
0.5	200	1	1.81	99.6	32	-	1.3	933	5.0	0.2	-	-	-	33	62	0.9
0.5	200	50	28.7	94.6	1430	-	65.3	3680	20.0	1.0	-	-	-	1300	2620	38.0
0.5	200	100	56.10	89.9	2860	-	157.0	7360	19.6	1.0	-	-	-	2640	4530	66.9
0.5	200	150	83.5	85.7	4280	-	236.0	11030	19.4	1.0	-	-	-	4090	7180	103.0
0.5	200	200	110.8	81.8	5680	-	311.0	13240	21.5	0.6	-	-	-	5350	9150	132.0
0.5	600	50	30.0	94.3	1430	-	65.3	3680	21.0	1.0	-	-	-	1300	2620	380.0
0.5	600	150	86.0	85.2	4280	-	236.0	11030	20.2	1.0	-	-	-	4090	7180	103.0
0.5	1200	50	33.7	93.7	1430	-	65.3	3680	23.5	1.0	-	-	-	1300	2620	38.0
0.5	1200	150	95.3	84.0	4280	-	236.0	11030	22.2	1.0	-	-	-	4090	7180	103.0
0.5	1800	50	38.9	92.8	1430	-	65.3	3680	27.0	1.0	-	-	-	1300	2620	38.0
0.5	1800	150	108.8	82.1	4280	-	236.0	11030	25.3	1.0	-	-	-	4090	7180	103.0
0.5	2500	1	5.35	98.9	27.5	28.5	1.3	-	-	-	1.2	16.9	4.0	33	62	0.9
0.5	2500	50	47.5	91.3	1430	-	65.3	3680	33.0	1.0	-	-	-	1300	2620	38.0
0.5	2500	100	89.4	84.8	2860	-	157.0	7360	31.1	1.0	-	-	-	2640	4530	66.9
0.5	2500	150	131.2	79.2	4280	-	236.0	11030	30.5	1.0	-	-	-	4090	7180	103.0
0.5	2500	200	172.9	74.3	5680	-	311.0	22070	20.1	0.8	-	-	-	5350	9150	132.0
7.0	600	1	29.2	99.6	384	405.0	16.0	-	-	-	7.0	15.8	6.5	397	735	10.5
7.0	600	100	80.5	98.8	2970	-	170.0	3460	24.4	1.0	-	-	-	2640	4530	66.9
7.0	600	200	136.4	98.1	5680	-	311.0	13240	26.4	0.6	-	-	-	5350	9150	132.0
7.0	1800	1	54.8	99.2	384	405.0	16.0	-	-	-	7.0	29.6	6.5	397	735	10.5
7.0	1800	100	120.1	98.3	2970	-	170.0	8460	36.4	1.0	-	-	-	2640	4530	66.9
7.0	1800	200	191.7	97.3	5948	-	338.0	15230	32.3	0.6	-	-	-	5350	9150	132.0
14.0	200	1	50.6	99.6	881	-	37.0	6530	20.0	1.0	-	-	-	794	1470	21.0
14.0	200	50	76.9	99.4	2430	-	136.8	9080	21.7	1.5	-	-	-	1820	3160	44.7
14.0	200	100	95.3	99.3	2970	-	170.0	8460	28.9	1.0	-	-	-	2640	4530	66.9
14.0	200	150	121.7	99.1	4450	-	256.0	12690	24.6	1.0	-	-	-	4090	7180	103.0
14.0	200	200	148.6	99.0	5940	-	338.0	15230	25.0	0.6	-	-	-	5350	9150	132.0
14.0	600	50	86.3	99.4	2430	-	136.0	9080	24.4	1.5	-	-	-	1820	3160	44.7
14.0	600	150	134.6	99.0	4450	-	256.0	12690	27.2	1.0	-	-	-	4090	7180	103.0

TABLE 1 (Cont.)

Average Power MW	Input Fre-quency Hz	Output Volt-age kV	Heat Load kW	Eff. %	Minimum Weight: Dry Weight lb	Wet Weight lb	Volume ft^3	Air Flow CFM	ΔT Air C°	ΔP Air in-H_2O	H_2O Flow GPM	ΔT H_2O C°	ΔP H_2O psi	Minimum Volume: Dry Weight lb	Wet Weight lb	Vol-ume ft^3
14.0	1200	50	108.3	99.2	2434	-	136.0	9080	30.6	1.5	-	-	-	1820	3160	44.7
14.0	1200	150	162.9	98.8	4450	-	256.0	12690	32.9	1.0	-	-	-	4090	7180	103.0
14.0	1800	50	145.7	99.0	1670	1762	126.0	Nat. Convection			22.5	19.9	6.5	1820	3160	44.7
14.0	1800	150	208.2	98.5	4930	-	296.0	23400	22.8	1.5	-	-	-	4720	8150	116.0
14.0	2500	1	149.5	98.9	768	810	32.0	-	-	-	16.8	33.8	8.0	794	1470	21.0
14.0	2500	50	190.4	98.7	1670	1760	126.0	Nat. Convection			22.5	26.3	6.5	1820	3160	44.7
14.0	2500	100	231.7	98.4	4870	-	345.0	18170	32.7	1.5	-	-	-	3100	5340	76.0
14.0	2500	150	275.2	98.1	7300	-	519.0	27350	25.9	1.5	-	-	-	4720	8150	116.0
14.0	2500	200	322.3	92.8	6570	-	391.0	3120	26.5	1.0	-	-	-	5350	9150	132.0
21.0	600	1	87.6	99.5	1170	1230	480.0	-	-	-	21.0	15.8	6.5	1190	2200	31.0
21.0	600	100	137.9	99.4	3280	-	196.0	15600	22.7	1.5	-	-	-	3100	5340	76.0
21.0	600	200	186.0	99.1	5940	-	338.0	15230	31.4	0.6	-	-	-	5350	9150	132.0
21.0	1800	1	164.0	99.2	1170	1230	48.0	-	-	-	21.0	29.6	6.5	1190	2200	31.0
21.0	1800	100	233.1	98.9	4870	-	345.0	18170	32.9	1.5	-	-	-	3100	5340	76.0
21.0	1800	200	299.2	98.6	6570	-	391.0	31200	24.6	1.0	-	-	-	5350	9150	132.0
30.0	200	1	108.5	99.6	1890	-	74.3	14000	20.0	1.0	-	-	-	1710	2940	42.0
30.0	200	50	155.2	99.5	1670	1760	126.0	Nat. Convection			22.5	22.7	6.5	1820	3160	44.7
30.0	200	100	160.0	99.5	4870	-	345.0	18170	22.7	1.5	-	-	-	3100	5340	76.0
30.0	200	150	179.8	99.4	4920	-	296.0	23400	19.7	1.5	-	-	-	4720	8150	116.0
30.0	200	200	200.9	99.3	5940	-	338.0	15230	33.8	0.6	-	-	-	5350	9150	132.0
30.0	600	50	172.4	99.4	1670	1760	126.0	Nat. Convection			22.5	25.5	6.5	1820	3160	44.7
30.0	600	150	200.6	99.3	4930	-	296.0	23400	22.0	1.5	-	-	-	4720	8150	116.0
30.0	1200	50	222.0	99.3	1672	1760	126.0	Nat. Convection			22.5	33.4	6.5	1820	3160	44.7
30.0	1200	150	257.9	99.2	7300	-	519.0	19250	34.3	1.5	-	-	-	4720	8150	116.0
30.0	1800	50	290.8	99.0	1670	1760	126.0	Nat. Convection			22.5	44.3	6.5	1820	3160	44.7
30.0	1800	150	344.3	98.9	7300	-	519.0	27250	32.4	1.5	-	-	-	4720	8150	116.0
30.0	2500	1	321.0	98.9	1680	1760	68.6	-	-	-	36.0	33.8	8.0	1710	2940	42.0
30.0	2500	50	375.0	98.8	1670	1760	126.0	Nat. Convection			31.5	41.0	19.5	1820	3160	44.7
30.0	2500	100	434.0	98.6	7370	-	491.0	41250	27.0	2.5	-	-	-	3100	5340	76.0
30.0	2500	150	467.4	98.5	7800	-	558.0	40880	29.3	1.5	-	-	-	4720	8150	116.0
30.0	2500	200	485.0	98.4	9730	-	688.0	54500	22.8	1.0	-	-	-	5960	10240	45.0

TABLE 2
INVERTER-FED RECTIFIER DESIGNS

Ave Power (MW)	Conversion Frequency (kHz)	Output Voltage (kV)	MIN WEIGHT DESIGNS: Wet Weight (lb)	Dry Weight (lb)	Volume (ft³)	Heat Load (kW)	Eff. %	Air Flow (CFM)	Air ΔT (C°)	Air ΔP (in-H₂O)	Water Flow (GPM)	Water ΔT (C°)	Water ΔP (lb/in²)	MIN VOLUME DESIGNS: Wet Weight (lb)	Dry Weight (lb)	Volume (ft³)	Heat Load (kW)	Δ T oil C°	Eff. %
0.5	5	40	-	80	4.6	5.5	98.9	404	35	1.0	-	-	-	242	119	2.94	5.5	6.1	98.9
0.5	5	80	-	153	10.3	5.4	98.9	324	43	0.7	-	-	-	382	200	4.5	6.0	4.7	98.8
0.5	5	120	-	225	17.6	4.2	99.2	303	35.5	0.5	-	-	-	584	303	6.92	5.25	2.7	99.0
0.5	5	160	-	298	24.9	5.6	98.9	404	35.5	0.5	-	-	-	797	404	9.54	7.0	2.6	98.6
0.5	5	200	-	370	32.6	7.0	98.6	506	35.5	0.5	-	-	-	1030	498	12.7	8.75	2.3	98.3
0.5	10	80	-	153	10.3	5.4	98.9	324	43	0.7	-	-	-	382	200	4.5	6.0	4.7	98.8
0.5	10	160	-	298	24.9	5.6	98.9	404	35.5	0.5	-	-	-	797	404	9.54	7.0	2.6	98.6
0.5	15	80	-	153	10.3	5.4	98.9	324	43	0.7	-	-	-	382	200	4.5	6.0	4.7	98.8
0.5	15	160	-	298	24.9	5.6	98.9	404	35.5	0.5	-	-	-	797	404	9.54	7.0	2.6	98.6
0.5	20	80	-	153	10.3	5.4	98.9	324	43	0.7	-	-	-	383	200	4.50	6.0	4.7	98.8
0.5	20	160	-	298	24.9	5.6	98.9	404	35.5	0.5	-	-	-	797	404	9.54	7.0	2.6	98.6
0.5	25	40	-	80	4.6	5.5	98.9	404	35	1	-	-	-	242	119	2.94	5.5	6.1	98.9
0.5	25	80	-	153	10.3	5.4	98.9	324	43	0.7	-	-	-	382	200	4.5	6.0	4.7	98.8
0.5	25	120	-	225	17.6	4.2	99.2	303	35.5	0.5	-	-	-	584	303	6.92	5.25	2.7	99.0
0.5	25	160	-	298	24.9	5.6	98.9	404	35.5	0.5	-	-	-	797	404	9.54	7.0	2.6	98.6
0.5	25	200	-	370	32.6	7.0	98.6	506	35.5	0.5	-	-	-	1032	498	12.7	8.75	2.3	98.3
7	10	40	-	724	33.2	60.8	99.1	3880	40	4.5	-	-	-	1070	510	12.5	58.5	15	99.2
7	10	120	-	1670	71.7	57	99.2	4600	32	4	-	-	-	2460	1340	26.5	52.5	6.7	99.3
7	10	200	-	790	47.7	56.9	99.2	3650	40	1.5	-	-	-	1460	726	17.7	54	10.6	99.2
7	20	40	-	724	33.2	60.8	99.1	3880	40	4.5	-	-	-	1070	510	12.5	60.5	15.6	99.1
7	20	120	-	1670	71.7	57	99.2	4600	32	4	-	-	-	2460	1340	26.5	54	7.2	99.2
7	20	200	-	790	47.7	56.9	99.2	3650	40	1.5	-	-	-	1460	726	17.7	54	10.6	99.2
14	5	40	-	1300	60.3	128	99.1	8450	39	1.5	-	-	-	1220	578	14.6	122	27.2	99.1
14	5	80	-	1430	73.7	122	99.1	7780	40	4.5	-	-	-	1810	923	20.4	115	18.3	99.1
14	5	120	-	1750	82.4	97.5	99.3	6240	40	8	-	-	-	2460	1340	26.5	96	12.2	99.3
14	5	160	-	2310	114	100	99.2	6130	42	4	-	-	-	3330	1800	35.9	94	8.9	99.3
14	5	200	-	2760	129.0	95	99.3	7670	32	4	-	-	-	4210.4	2270	45.9	90	6.7	99.4
14	10	80	-	1430	73.7	122	99.1	7780	40	4.5	-	-	-	1810	923	20.4	115	18.3	99.2
14	10	160	-	2310	114	100	99.3	6130	42	4	-	-	-	3330	1800	35.8	96	8.9	99.3
14	15	80	-	1430	73.7	122	99.1	7780	40	4.5	-	-	-	1810	923	20.4	117	18.9	99.2
14	15	160	-	2310	114	100	99.3	6130	42	4	-	-	-	3330	1800	35.8	96	8.9	99.3
14	20	80	-	1430	73.7	122	99.1	7780	40	4.5	-	-	-	1810	923	20.4	118	19.4	99.2
14	20	160	-	2310	114	100	99.3	6130	42	4	-	-	-	3330	1800	35.8	98	9.4	99.3
14	25	40	-	1300	60.3	143	99.0	9910	37	1.75	-	-	-	1220	578	14.6	138	30.7	99.0
14	25	80	-	1430	73.7	122	99.1	7780	40	4.5	-	-	-	1810	923	20.4	118	19.4	99.2
14	25	120	-	1750	82.4	97.5	99.3	6240	40	8	-	-	-	2460	1340	26.5	100	12.8	99.2
14	25	160	-	2310	114	100	99.3	6130	42	4	-	-	-	3330	1800	35.8	98	9.4	99.3
14	25	200	-	2760	129	95	99.3	7670	32	4	-	-	-	4210.4	2220	46.0	95	6.7	99.3
21	10	40	1440	1250	127	208	99.0	Natural Convection			128	5.85	11	1300	688	14.9	199	32.8	99.1
21	10	120	-	2150	114	183	99.1	11,660	40	4.5	-	-	-	2720	1410	30.3	172	18.9	99.2
21	10	200	-	2880	147	162	99.2	10,400	40	8	-	-	-	4210	2220	46	145	10.5	99.3
21	20	40	1440	1250	127	215	99.0	Natural Convection			128	6.1	11	1300	688	14.9	206	34	99.0
21	20	120	-	2150	114	182	99.1	11,660	40	4.5	-	-	-	2720	1410	30.3	172.5	19	99.2
21	20	200	-	2880	147	162	99.2	10,400	40	8	-	-	-	4210	2220	46	145	10.5	99.3
30	5	40	1440	1250	127	318	99.0	Natural Convection			128	9.1	11	1380	729	15.9	311	65.5	99.0
30	5	80	-	2590	128	278	99.1	19265	37	1.75	-	-	-	2070	1050	23.7	261	33.3	99.1
30	5	120	-	2730	129	261	99.1	16890	40	1.5	-	-	-	2800	1460	31.3	240	25.6	99.2
30	5	160	-	2840	150	243	99.2	15550	40	4.5	-	-	-	3620	1850	40.9	220	17.8	99.3
30	5	200	-	3270	161	242	99.2	15330	41	2	-	-	-	4180	2200	45.2	222	16.1	99.3
30	10	80	-	2590	128	278	99.1	19260	37	1.75	-	-	-	2070	1050	23.7	265	33.3	99.1
30	10	160	-	2840	150	243	99.2	15550	40	4.5	-	-	-	3620	1850	40.1	222	17.8	99.3
30	15	80	-	2590	128	278	99.1	19260	37	1.75	-	-	-	2070	1050	23.7	269	38.9	99.1
30	15	160	-	2840	150	243	99.2	15550	40	4.5	-	-	-	3620	1850	40.9	226	17.8	99.2
30	20	80	-	2590	128	278	99.1	19260	37	1.75	-	-	-	2070	1050	23.7	273	34.4	99.1
30	20	160	-	2840	150	243	99.2	15550	40	4.5	-	-	-	3620	1850	40.9	230	18.3	99.2
30	25	40	1440	1250	127	340	98.9	Natural Convection			128	9.8	11	1380	729	15.9	333	69.7*	98.9
30	25	80	-	2590	128	278	99.1	19260	37	1.75	-	-	-	2070	1050	23.7	276	35	99.1
30	25	120	-	2730	129	261	99.1	16890	40	1.5	-	-	-	2800	1460	31.3	255	27.2	99.2
30	25	160	-	2840	150	243	99.2	15550	40	4.5	-	-	-	3620	1850	40.9	234	18.9	99.2
30	25	200	-	3270	161	242	99.2	15330	41	2	-	-	-	4180	2200	45.23	225	16.1	99.3

*Oil Flow Recommended

TABLE 3
INVERTER DESIGN RESULTS

Ave Power (MW)	Input Voltage (kV)	Conversion Frequency (kHz)	Output Voltage (kV)	TOTAL VOLUME Min Wt. (ft^3)	TOTAL VOLUME Min Vol. (ft^3)	DRY WEIGHT Min Wt. (lb)	DRY WEIGHT Min Vol. (lb)	WET WEIGHT Min Wt. (lb)	WET WEIGHT Min Vol. (lb)	Efficiency %	Heat Load (kW)	Air Flow (CFM) @ 1 in. H_2O, 20 C^O ΔT Min Weight	H_2O FLOW MIN WEIGHT (GPM)	H_2O FLOW MIN WEIGHT ΔT (C^O)	H_2O FLOW MIN WEIGHT ΔP (PSI)	H_2O FLOW MIN VOLUME (GPM)	H_2O FLOW MIN VOLUME ΔT (C^O)	H_2O FLOW MIN VOLUME ΔP (PSI)
0.5	1	5	40	23.2	20.6	781	721	809	1,340	89.8	56.9	828	2.5	32.9	30	0.5	12.9	1
0.5	1	5	80	23.8	21.2	804	727	848	1,360	89.0	62.1	828	2.5	32.9	30	0.5	12.9	1
0.5	1	5	120	24.6	21.8	829	733	896	1,390	88.9	62.5	828	2.5	32.9	30	0.5	12.9	1
0.5	1	5	160	25.2	22.4	849	739	938	1,410	88.8	63.1	828	2.5	32.9	30	0.5	12.9	1
0.5	1	5	200	25.9	23.0	891	747	1,040	1,440	88.7	63.6	828	2.5	32.9	30	0.5	12.9	1
0.5	1	10	40	18.1	16.1	603	584	635	1,050	89.9	56.4	1,010	4.0	23.3	11	0.5	19.7	1
0.5	1	10	80	18.9	16.8	626	589	676	1,090	89.8	56.7	1,010	4.0	23.3	11	0.5	19.7	1
0.5	1	10	120	19.8	17.6	650	594	[illegible]	1,130	89.8	57.1	1,010	4.0	23.3	11	0.5	19.7	1
0.5	1	10	160	21.1	18.8	678	599	751	1,200	89.7	57.5	1,010	4.0	23.3	11	0.5	19.7	1
0.5	1	10	200	21.6	19.2	706	606	869	1,210	89.6	58.0	1,010	4.0	23.3	11	0.5	19.7	1
0.5	1	15	120	15.9	14.2	526	523	586	915	89.9	56.0	1,030	6.0	17.4	22	0.5	26.7	1
0.5	1	25	120	25.0	22.2	713	757	817	1,400	85.2	86.8	1,770	14	13.5	31	1	37.9	1
7	7	10	40	356	292	11,580	11,240	11,970	21,300	90.7	715	13,770	24	40.9	20	9	36.4	1.5
7	7	10	120	356	292	11,630	11,290	12,180	21,350	90.6	722	13,770	24	40.9	20	9	36.4	1.5
7	7	10	200	356	292	11,690	11,350	12,530	21,410	90.6	729	13,770	24	40.9	20	9	36.4	1.5
7	1	10	200	302	257	9,880	8,320	12,170	16,180	89.6	812	14,100	56	30.7	11	7	19.7	1
14	1	5	40	649	541	21,870	19,580	22,650	35,220	89.8	1590	23,180	70	32.9	30	14	12.9	1
14	1	5	80	668	557	22,510	19,740	23,740	35,870	89.0	1740	23,180	70	32.9	30	14	12.9	1
14	1	5	120	688	574	23,210	19,910	25,090	36,560	88.9	1750	23,180	70	32.9	30	14	12.9	1
14	1	5	160	704	589	23,770	20,070	26,260	37,160	88.8	1770	23,180	70	32.9	30	14	12.9	1
14	1	5	200	725	605	24,950	20,290	29,060	37,820	88.7	1780	23,180	70	32.9	30	14	12.9	1
14	1	15	120	446	372	14,730	14,200	16,410	24,080	89.9	1570	28,870	168	17.4	22	14	26.7	1
14	1	25	120	700	584	19,960	20,560	22,880	36,980	85.2	2430	49,670	392	13.5	31	28	37.9	1
21	7	10	40	1070	876	34,740	33,720	35,910	63,880	90.7	2150	41,320	72	40.9	20	27	36.4	1.5
21	7	10	120	1070	876	34,900	33,870	36,540	64,040	90.6	2170	41,320	72	40.9	20	27	36.4	1.5
21	7	10	200	1070	876	35,080	34,050	37,600	64,220	90.6	2190	41,320	72	40.9	20	27	36.4	1.5
30	1	5	40	1390	1139	46,860	41,600	48,540	74,110	89.8	3420	49,680	150	32.9	30	30	12.9	1
30	1	5	80	1431	1172	48,240	41,940	50,880	75,490	89.0	3720	49,680	150	32.9	30	30	12.9	1
30	1	5	120	1474	1207	49,740	42,290	53,760	76,940	88.9	3750	49,680	150	32.9	30	30	12.9	1
30	1	5	160	1509	1240	50,940	42,630	56,280	78,200	88.8	3790	49,680	150	32.9	30	30	12.9	1
30	1	5	200	1553	1273	53,460	43,100	62,280	79,590	88.7	3820	49,680	150	32.9	30	30	12.9	1
30	1	15	120	956	784	31,560	30,170	35,160	50,680	89.9	3360	61,860	360	17.4	22	30	26.7	1
30	1	25	120	1500	1230	42,780	43,670	49,020	77,820	85.2	5210	106,440	840	13.5	31	60	37.9	1

TABLE 4

PFN DESIGN RESULTS

Design No.	Avg. Power (MW)	Energy (KJ/P)	Rep. Rate (Hz)	Pulse Width (μS)	Total Volume		(Dry) Total Weight		(Wet) Total Weight		Eff. %	Heat Load Total kW	Air Flow (CFM)	H₂O Flow (GPM)	
					Min. Wt. (ft^3)	Min. Vol. (ft^3)	Min. Wt. (lb)	Min. Vol. (lb)	Min. Wt. (lb)	Min. Vol. (lb)			@1 in H_2O, 40C°ΔT Min. Weight	@4PSI, 40C°ΔT Min. Weight	Min. Volume
1	0.5	10	50	5	39.2	30.9	842	872	857	1800	89.7	57.5	860	1.57	1.06
2	0.5	10	50	10	30.3	23.9	695	715	710	1430	90.6	51.9	730	1.22	1.06
3	0.5	10	50	20	30.3	23.9	711	732	726	1450	90.8	50.8	730	1.12	1.06
4	0.5	10	50	30	31.5	24.9	660	679	676	1410	90.8	50.8	730	1.12	1.06
5	0.5	10	50	40	32.8	25.8	675	694	692	1460	90.8	50.8	730	1.11	1.06
6	7	25	280	5	129	89.2	2630	2710	2770	5770	94.3	427	7440	18.9	14.8
7	7	25	280	10	129	89.2	2710	2790	2850	5850	94.6	397	7440	16.1	14.8
8	7	25	280	20	129	89.2	2560	2630	2700	5690	94.7	388	7440	15.3	14.8
9	7	25	280	30	135	92.8	2640	2710	2780	5910	94.7	388	7440	15.3	14.8
10	7	25	280	40	140	96.4	2720	2800	2850	6130	94.7	388	7440	15.3	14.8
11	7	50	140	5	194	122	3930	4040	4100	8220	93.8	459	7840	19.1	14.3
12	7	50	140	10	180	113	3720	3820	3880	7690	94.5	408	7300	15.1	13.8
13	7	50	140	20	180	113	3520	3620	3670	7480	94.6	400	7300	14.3	13.8
14	7	50	140	30	163	102	3220	3320	3390	6780	94.6	400	7300	14.4	13.8
15	7	50	140	40	170	106	3280	3380	3450	6990	94.6	400	7300	14.4	13.8
16	7	75	93.3	5	291	182	5840	6010	5980	12450	93.6	482	8470	19.1	14.3
17	7	75	93.3	10	221	138	4460	4590	4660	9390	93.2	509	7701	20.3	19.6
18	7	75	93.3	20	206	129	4340	4460	4480	8990	93.6	478	7310	14.7	14.2
19	7	75	93.3	30	214	134	4460	4590	4620	9320	93.6	478	7310	14.7	14.2
20	7	75	93.3	40	222	139	4600	4730	4770	9660	93.6	478	7310	14.7	14.2
21	7	100	70	5	415	267	7330	7540	7520	17350	92.4	579	9310	19.1	14.3
22	7	100	70	10	295	190	5880	6050	6030	12880	93.2	512	7760	15.1	13.5
23	7	100	70	20	290	187	5790	5960	5970	12680	93.4	496	7280	14.4	13.8
24	7	100	70	30	240	154	5070	5220	5250	10720	93.4	496	7280	14.4	13.8
25	7	100	70	40	249	160	5010	5150	5200	10880	93.4	496	7280	14.4	13.8
26	14	50	280	5	277	175	5260	5400	5540	11700	94.3	848	14530	37.8	29.7
27	14	50	280	10	277	175	5410	5570	5700	11860	94.7	789	14530	32.3	29.7
28	14	50	280	20	277	175	5100	5250	5380	11540	94.8	771	14530	30.6	29.7
29	14	50	280	30	288	183	5260	5420	5520	11990	94.8	771	14530	30.6	29.7
30	14	50	280	40	299	189	5430	5590	5740	12420	94.8	771	14530	30.6	29.7
31	14	75	186.6	5	301	193	6240	6420	6490	13400	94.1	880	14610	38.1	28.5
32	14	75	186.6	10	295	190	5930	6100	6200	12940	94.7	790	14390	31.3	28.2
33	14	75	186.6	20	295	190	5710	5870	5990	12720	94.8	768	14390	29.3	28.2
34	14	75	186.6	30	307	197	5840	6010	6130	13140	94.8	768	14390	29.3	28.2
35	14	75	186.6	40	319	205	5980	6150	6270	13570	94.8	768	14390	29.3	28.2
36	14	100	140	5	415	267	7780	8000	8040	17810	94.0	893	15390	38.2	28.6
37	14	100	140	10	386	256	7420	7640	7740	17030	94.7	790	14320	30.1	27.6
38	14	100	140	20	386	256	7140	7340	7440	16730	94.8	774	14320	28.5	27.6
39	14	100	140	30	327	210	6440	6620	6770	14240	94.8	776	14320	28.8	27.6
40	14	100	140	40	339	218	6550	6740	6900	14670	94.8	776	14320	28.7	27.6
41	21	50	420	5	384	247	6880	7070	7230	16100	94.7	1170	19940	54.1	38.2
42	21	50	420	10	384	247	7020	7220	7390	15950	95.1	1090	19940	45.9	38.2
43	21	50	420	20	384	247	6530	6720	6890	15450	95.1	1060	19940	43.5	38.2
44	21	50	420	30	399	257	6820	7010	7190	16420	95.1	1060	19940	43.4	38.2
45	21	50	420	40	415	267	7100	7310	7500	17100	95.2	1060	19940	43.3	38.2
46	21	75	280	5	388	251	7360	7570	7790	16770	94.2	1285	20040	60.6	44.6
47	21	75	280	10	388	251	7600	7810	8030	17010	94.6	1200	20040	52.3	44.6
48	21	75	280	20	388	251	7130	7340	7560	16530	94.7	1170	20040	49.7	44.6
49	21	75	280	30	404	262	7380	7590	7760	17180	94.7	1170	20040	49.7	44.6
50	21	75	280	40	420	271	7620	7840	8090	17820	94.7	1170	20040	49.7	44.6
51	21	100	210	5	415	267	7760	7980	8180	17790	94.2	1290	20040	63.2	45.0
52	21	100	210	10	415	267	7750	7970	8170	17780	94.6	1190	20040	53.4	45.0
53	21	100	210	20	415	267	7420	7640	7840	17440	94.8	1140	19900	48.5	43.0
54	21	100	210	30	432	278	7630	7850	8070	18080	94.9	1140	19900	48.4	43.0
55	21	100	210	40	449	289	7850	8070	8300	18710	94.9	1140	19900	48.3	43.0
56	30	75	400	5	512	329	8840	9090	9310	21290	94.3	1810	27640	73.8	53.3
57	30	75	400	10	512	329	9030	9290	9520	21490	94.6	1700	27640	63.4	53.3
58	30	75	400	20	512	329	8480	8720	9060	20930	94.7	1680	27720	61.6	54.5
59	30	75	400	30	532	343	8860	9120	9460	21840	94.7	1680	27720	61.5	54.5
60	30	75	400	40	553	356	9240	9510	9870	22740	94.7	1680	27720	61.4	54.5
61	30	100	300	5	518	331	9330	9600	9920	21860	94.6	1720	25560	93.9	63.6
62	30	100	300	10	518	331	9650	9920	10240	22180	95.0	1590	25560	81.9	63.6
63	30	100	300	20	518	331	9030	9280	9610	21550	95.1	1550	25560	78.5	63.6
64	30	100	300	30	539	344	9350	9620	9960	22400	95.1	1550	25560	78.3	63.6
65	30	100	300	40	560	357	9680	9960	10310	23260	95.1	1550	25560	78.2	63.6

SECTION III

PHASE III - SPACEBORNE POWER CONDITIONING SUBSYSTEMS

1. BACKGROUND

Four minimum weight subsystem designs from Phase II have been reconsidered for spaceborne applications with modified duty. The design points are described in Table 5.

The principal tasks undertaken in evaluating these designs for space were the management of heat dissipation without air, oil or water cooling and the isolation of high voltage in the far-from-perfect vacuum of a space vehicle or platform environment. Details of ionizing radiation and launch environments were not considered.

Initially, the approach followed in the thermal evaluation was to establish a feasible concept for controlling the temperature of the critical item in each subsystem. Subsequently, it was found that repackaging of the continuously operating subsystems would be necessary.

In each case, a passive conduction/radiation approach was found to suffice for heat transfer from the subsystems to a space vehicle wall assumed to be kept at a constant temperature by means of external radiators and/or auxiliary heating. Although wall temperatures from +20°C to -20°C were briefly studied, a temperature of +20°C was usually selected for evaluation as representing a realistic minimum surface area in most cases.

Solar loading on the space vehicle was considered negligible because of shielding by solar panels.

TABLE 5

PHASE III DESIGN POINTS

Subsystem	Ave. Power (MW)	Frequency (kHz)	Output (kV)	Duty
Three-Phase Rectifier	21 7	0.6 1.8	100 1	Intermittent, 2 min on, 24 hr off
Inverter-Fed Rectifier	0.5	20	80	Continuous
Inverter	0.5	15	120	Continuous

2. THREE-PHASE RECTIFIER

Two three-phase rectifier subsystems were considered which differed in operating power, frequency and voltage but had an identical operating duty of two min ON, 24 hr OFF.

a. Three-phase Rectifier (21 MW)

This subsystem consists of 72 modules each containing ten SCRs as illustrated in Figure 2. The critical component is the GE type C613 SCR which accounts for 70 percent of the 138 kW heat load of the subsystem.

The technique for heat transfer in space is to assume that the heat dissipated in each SCR during the ON period is stored in its associated heat sink for later transfer during the OFF period. Heat is transferred between the aluminum heat sinks and electrically isolated by means of beryllia (BeO) rods. The end plates of each module radiate heat to the spacecraft walls which are assumed to be maintained at a constant temperature and connected to external radiators.

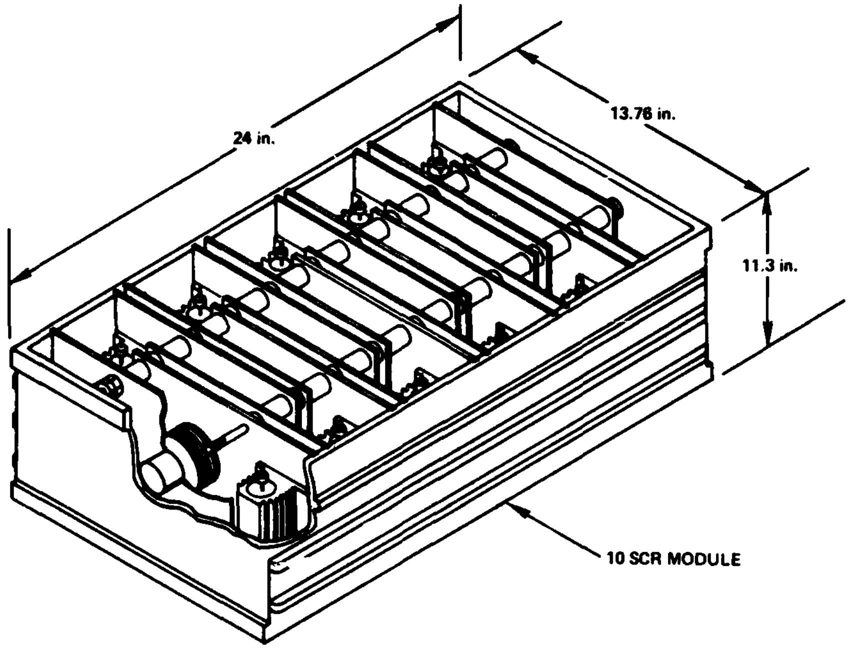

Figure 2 - Three-Phase Rectifier 10 SCR Module

(1) Steady-state Analysis Summary

The external vehicle radiating area for a total rectifier load of 655 BTU/hr over the 24 hr OFF period varies from 5.4 ft^2 at +20°C to 9.7 ft^2 at -20°C.

Heat is conducted in both directions in each ten SCR module to end faces 13.76 in. x 11.3 in. by means of a beryllia rod of thermal conductivity 60 BTU/hr- ft-°F. Analysis results in a maximum module face temperature of 104°C end plate to a 20°C wall.

The required weight of BeO is calculated to be 0.75 lb for a rod of 0.002 ft^2 in cross section by 2 ft long with a density of 187.7 lb/ft^3 for each 10-SCR module. The total BeO weight for the 72-module rectifier is 54 lb. The total 21-MW subsystem would weigh 3334 lb and have a volume of 196 ft^3. This weight is distributed among heatsinks (26%), compensating resistors (21%), SCR assemblies including triggers (17%) and miscellaneous hardware and structure (34%). The BeO added for operation in the space environment comprises only 2% of the total weight.

(2) Transient Analysis Summary

A multimode thermal computer model was constructed using the dimensions and properties from the previous steady-state analysis to check the validity of the assumed +20°C constant vehicle heat sink. The results for a single 24-hr cycle given in Figure 3 show the average vehicle wall temperature is more likely to be 24°C (75°F). Also, all the component temperatures did not return to the 20°C (68°F) assumed initial value which indicates the necessity for increased thermal conductance or heat sink capacity.

To examine the model sensitivity to cooldown, two parameters were arbitrarily varied. The responses to an increase of a factor of ten in vehicle heat sink area and a factor of two in BeO rod conductance are shown separately in Figure 4.

Neither variation is considered unrealistic since the radiator wall size would increase to only ~ 54 ft^2 and the initial BeO conductivity and cross section have been conservatively chosen. Clearly, a more detailed analysis of all components of

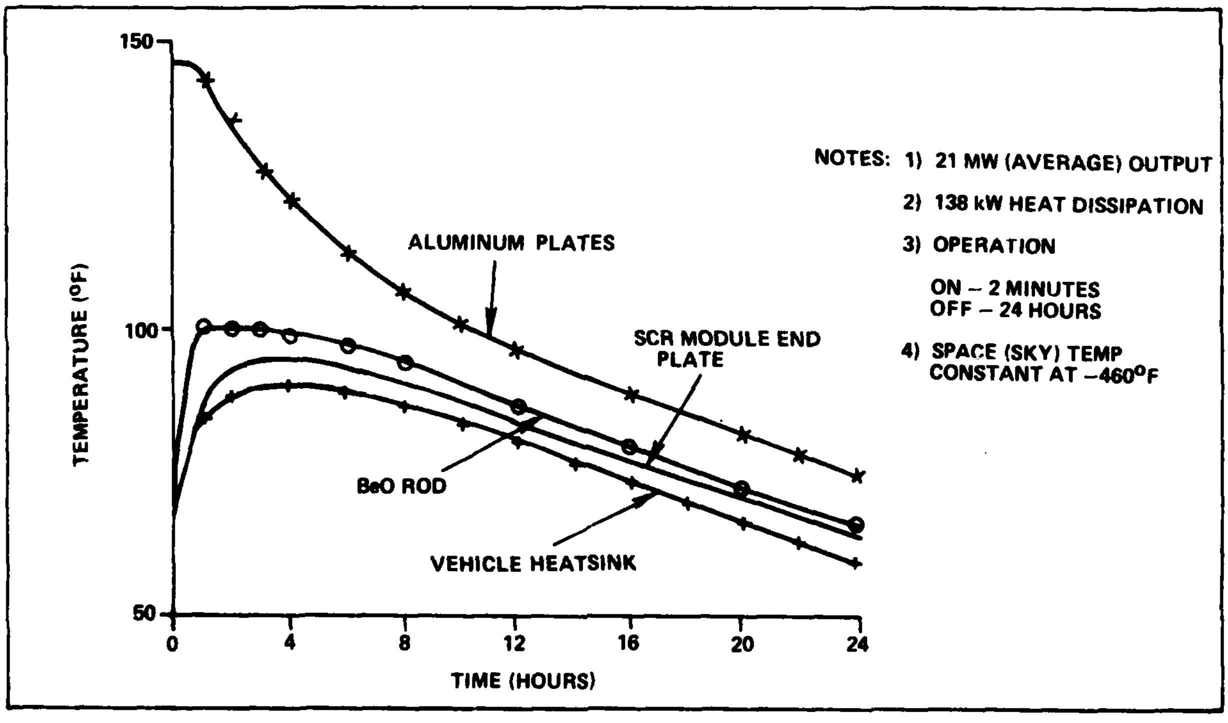

Figure 3 - Three-Phase Rectifier Plate Thermal Transient Model-One Cycle

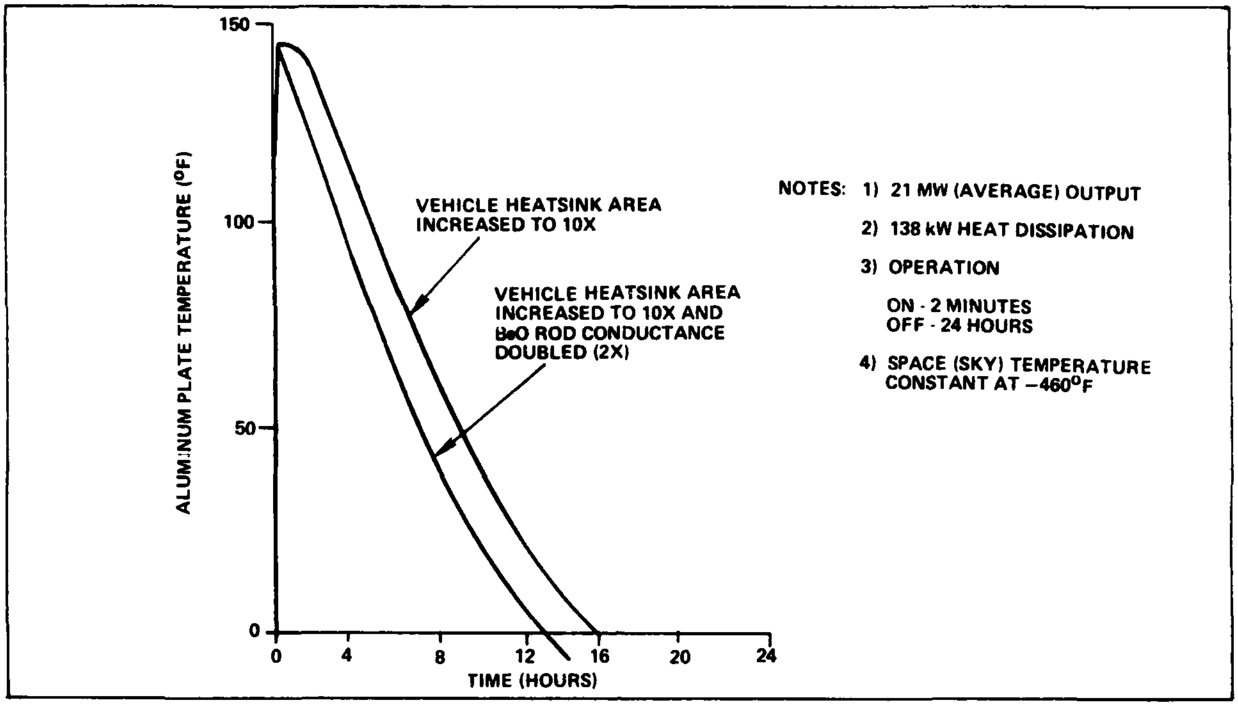

Figure 4 - Three-Phase Rectifier Plate Thermal Transient Analysis

the thermal system should be carried out until equilibrium is achieved. However, the point of this figure is that sufficient flexibility in design parameters clearly exists for the 20°C wall temperature to be attainable.

b. **Three-phase Rectifier (7 MW)**

This subsystem consists of 14 modules, each containing six SCRs as illustrated in Figure 5. The module has been repackaged with larger adiabatic heat sinks to replace the water-cooling which was used in the airborne design. As in the 21-MW design the critical component is again the GE type C613 SCR which, because of the higher frequency operation, accounts for more than 90 percent of 55 kW heat load of this subsystem.

The technique for heat transfer in space is similar to that used for the 21-MW design in which heat is stored in the heat sinks during the ON period and conducted to the end plates during the OFF period by means of BeO rods. The end plates then radiate this heat to the spacecraft walls which are connected to external radiators.

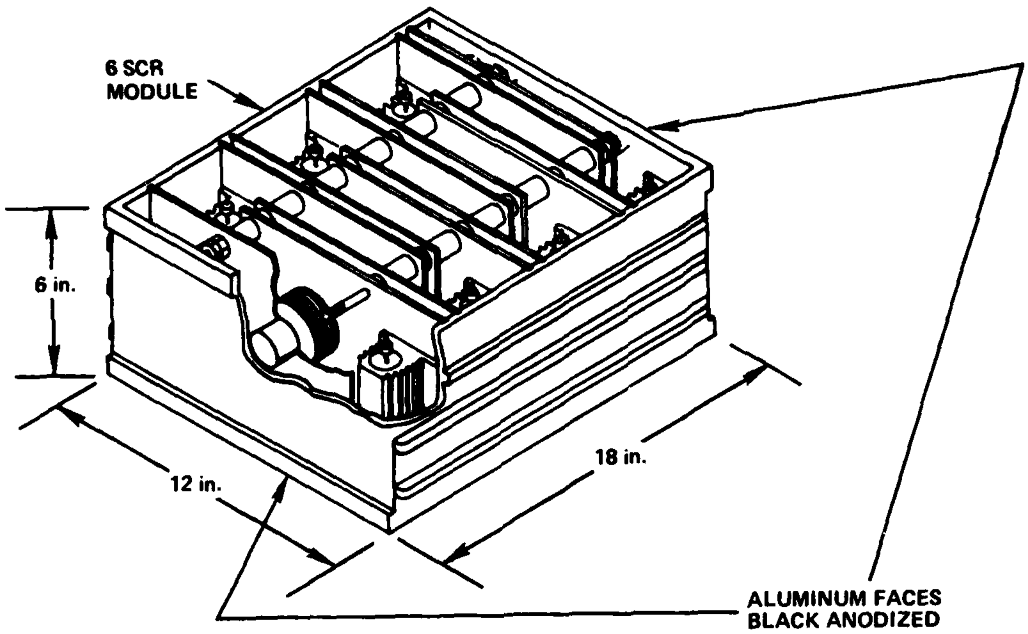

Figure 5 - Three-Phase Rectifier 6 SCR Module

The external vehicle radiative area required for a total rectifier load of 260 BTU/hr to the +20°C wall over the 24 hr OFF period is 2.2 ft^2. This analysis shows a maximum module end face temperature of 79°C with an allowed junction temperature of 125°C. The available end plate area of 72 in.^{2} is again substantially larger than the minimum area of ~10 in.^{2} required for radiation from a 79°C end plate to a 20°C wall.

The required weight of BeO is calculated on the basis of a rod 0.004 ft^2 in cross section by 1.5 ft long with a density of 187.7 lb/ft^3 for each 6-SCR module. The total BeO weight for the 14-module rectifier is 15.7 lb.

The total subsystem would weigh 534 lb and have a volume of 16.3 ft^3. This weight is distributed among heat sinks (44%), compensating resistors (15%), SCR assemblies with triggers (12%) and miscellaneous hardware and structure (26%). The added BeO comprises only 3% of the total weight.

3. INVERTER-FED RECTIFIER

The airborne 500-kW point design was repackaged because of the increased duty from intermittent to continuous operation. The critical items were the thousand diodes (IR type 12FL100S05) packaged to rectify a 20 kHz input voltage source to 80 kVdc.

Each rectifier module contained a pair of diodes (5.1 W dissipation per diode) and RC compensation (0.3 W per resistor) resulting in an initial subsystem heat load of 5.4 kW. The repackaging approach utilized an aluminum plate heat sink attached to each diode and brazed to the metallized surface of a BeO block. The block is clamped to the spacecraft wall from which the heat is radiated. Sketches of the module and a possible clamping method are shown in Figures 6 and 7.

The heat load of 5.4 kW is based on a diode junction temperature of 100°C. Analysis of heat conduction and radiation showed that a spacecraft wall temperature of 84°C would result and a radiating area of 70 ft^2 would be required.

In order to minimize the required radiating area a thermal analysis was performed in which the diode junction temperature was varied over the range from 100°C to the maximum allowable junction temperature of 150°C. An increase in junction temperature resulted in greater diode dissipation and a relatively higher spacecraft wall temperature which consequently improved the radiating efficiency.

From this analysis an optimum junction operating temperature in the range of 120°C was chosen with a resulting subsystem dissipation of 5.8 to 6.6 kW. A radiating area of about 60 ft^2 with a wall temperature of $\sim$100°C was required. A 20°C wall temperature would require a radiating area of 155 ft^2.

The continuously operating inverter-fed rectifier would be 77 in. by 112 in. by 4.5 in. high, occupying a volume of 22.4 ft^3 and weighing 1035 lb, not including the weight of the spacecraft wall. At an average dissipation of 6.2 kW, the efficiency would be almost 99 percent. The weight of this subsystem is primarily concentrated in the BeO (52%) and epoxy potting (20%) with only 3% in the diodes and the remaining 25 percent in miscellaneous small components and structure.

4. INVERTER

The change from airborne to space environment and from intermittent to continuous operation required major modifications and repackaging of the design of a 500-kW, 15-kHz inverter with one kV input and a 120-kV output. This design point was chosen for comparison with a similar design prepared during Phase II for an airborne environment. The effect of reducing the operating power and input voltage is discussed later in this section.

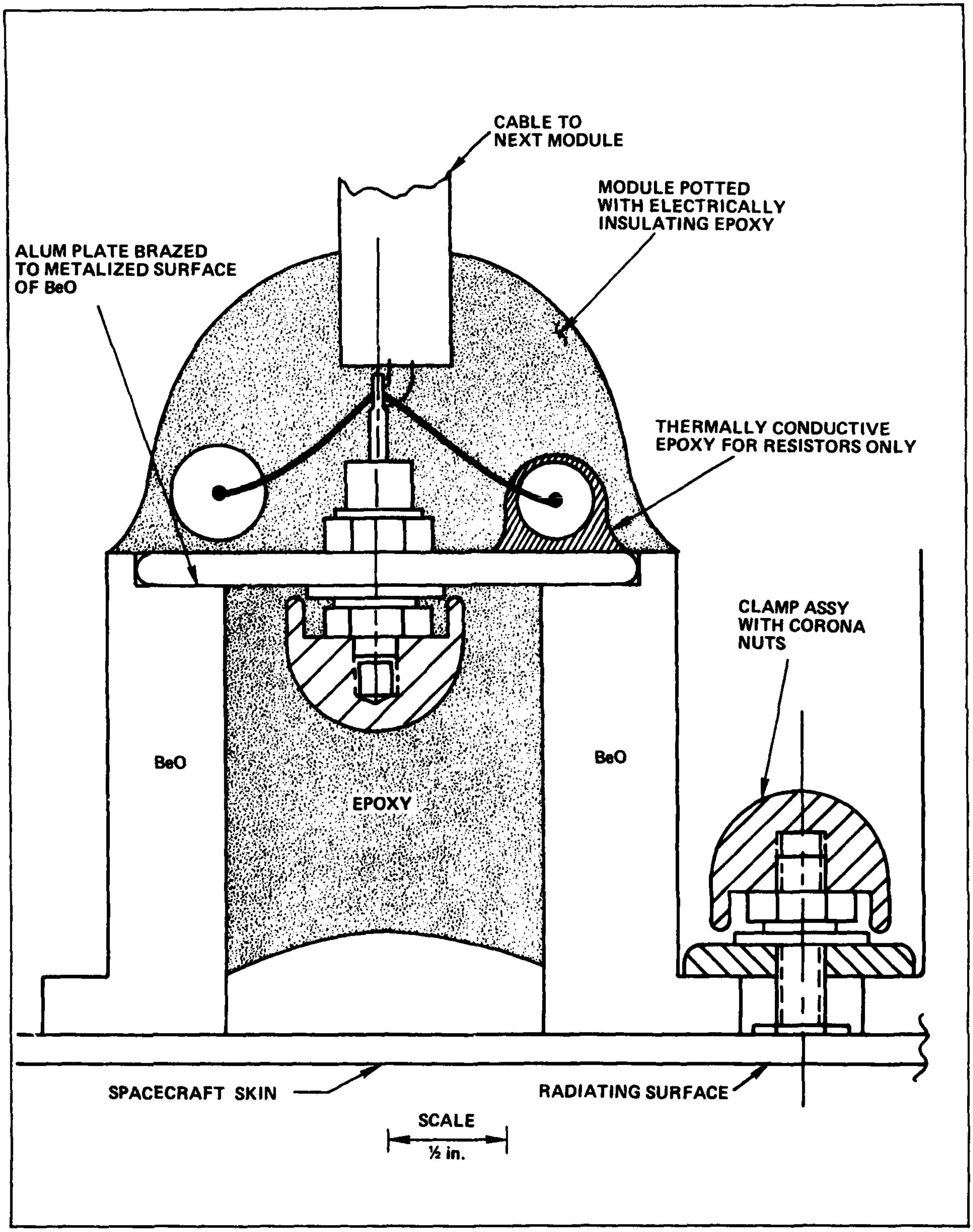

Figure 6 - Inverter-Fed Rectifier Module

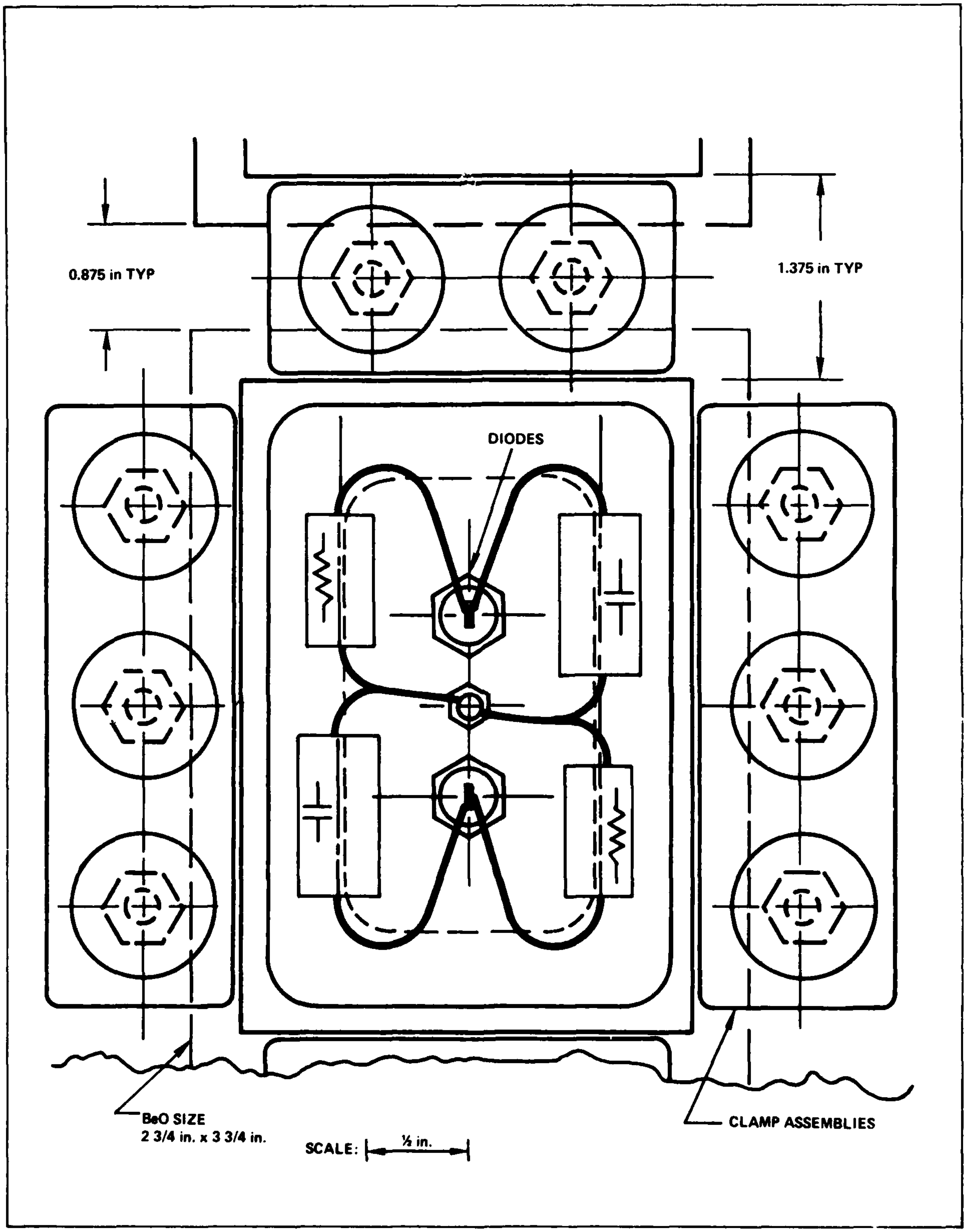

Figure 7 - Top View Of Module

The implication of these changes is first of all, the redesign of the magnetic components, specifically the four linear reactors, the four saturable reactors and the output power transformer. These components were originally designed for adiabatic operation, 180°C temperature rise in two min operation and changed to 150°C temperature rise in continuous operation. The adiabatic design versions would have reached a final continuous operating temperature from 800°C to 1000°C. The redesign process therefore required that from 80 to 90 percent of the adiabatic heat loss be removed for continuous operation, thereby increasing the subsystem efficiency.

Secondly, all inverter components were redesigned or reconfigured to include high thermal conductivity solid materials such as aluminum and beryllium oxide (BeO) to conduct the total heat load to the spacecraft wall.

In the process of this general redesign all liquid-filled, liquid-cooled and/or liquid-immersed components were replaced by solid encapsulants such as epoxy and the solid, thermally conductive materials known to be consistent with the life and reliability requirements for long term spacecraft operation.

a. **Spaceborne 500-kW Inverter**

Reduction of heat loss in the magnetic components was accomplished in the 500-kW inverter as follows:

	Loss (Watts)	
Component	Adiabatic	Continuous
Saturable Reactor (each)	880	175
Linear Reactor (each)	3240	730
Output Transformer	6400	700

Thus the total magnetic component loss was reduced from 22.9 kW to 4.3 kW, or approximately an 80 percent reduction. This effort was accomplished by employing improved core materials such as Metglas 2605SC, a high permeability, low loss, square B-H loop material ideally suited for the saturable reactor as a single turn toroidal core located directly on the 1000-A conductor. In the case of the linear reactor and the output transformer, increased conductor size was required which necessitated significant increases in component size and weight as follows:

	Core and Coil Weight (lb)	
Component	Adiabatic	Continuous
Saturable Reactor (each)	1.3	0.65
Linear Reactor (each)	8.25	41.5
Output Transformer	32.6	117.8

The net magnetic component weight (core and coil only without heat sinks or cooling provisions) increased from 70.8 lb to 286.4 lb or four times the original weight, consistent at least on a first order basis with removing 80 percent of the heat loss. However, significant advantages accrue to the spacecraft radiators and cooling approach by the removal of 18.6 kW from the initial airborne system heat load of 56 kW.

The low voltage isolation required everywhere, 1770 Vrms, is ideally suited for solid aluminum heat sinking directly with insulating materials such as the elastomer CHO-THERM ® (Reference (2)) or BeO required only in thin sections. The sole exception to this practice is the secondary winding of the power transformer, rated at 100 kVrms for a capacitive input filter, or 10 kV each for the ten "pie" windings physically stacked upon each other with insulating rings of BeO between them to conduct the secondary winding copper loss of 80 W out of the coil. An additional BeO block external to the coil is used to further conduct heat to the spacecraft wall.

Interestingly enough, in replacing the metal-cased, liquid-filled capacitors which had a terminal limitation of 175 A, it was possible to configure similar epoxy-encapsulated, polypropylene capacitors using extended copper foils directly attached to copper terminal plates/heat-sinks capable of carrrying the full 350 A required in a single unit. Thus the 16 resonating capacitors are reduced to eight with the accompanying reduction in hardware, connections, etc. The coupling capacitor is similar, so an additional like capacitor is used in that application as well.

In the original intermittent duty airborne design, the major heat loss, 24 kW of the total of 56 kW, was dissipated in four series strings of four SCRs each dissipating 1500 W and actively water cooled.

For this spaceborne requirement an additional parallel string of four SCRs was added to each of the existing strings for a revised total of 32 SCRs, but with individual losses of 570 W each, thereby reducing the dissipation at each SCR by 62 percent and the total spacecraft heat load by 5760 W.

As a result of the redesign effort outlined above the total power supply heat loss was reduced from approximately 56 kW to 30 kW, a not insignficant 45 percent reduction in required spacecraft heat radiator area. Inverter power supply efficiency was thus increased from 90 to 94 percent as a result of the redesign effort as well.

A schematic of this inverter as modified for operation in space is given in Figure 8. Preliminary layouts of the inverter (one-quarter of circuit) and the output circuit are given in Figures 9 and 10, respectively. Each quarter inverter is estimated to weight 229 lb and occupy a volume of 4.2 ft^3. The total inverter subsystem therefore weighs 1107 lb and occupies a volume of 18.8 ft^3. A 20°C wall temperature requires a radiating area of 845 ft^2. The principal contributors to the inverter weight are the linear reactors (30%), mounting plates (20%), SCR assemblies (15%) and the output transformer (15%). The remaining 20% of the weight is made up of miscelleneous small components and hardware.

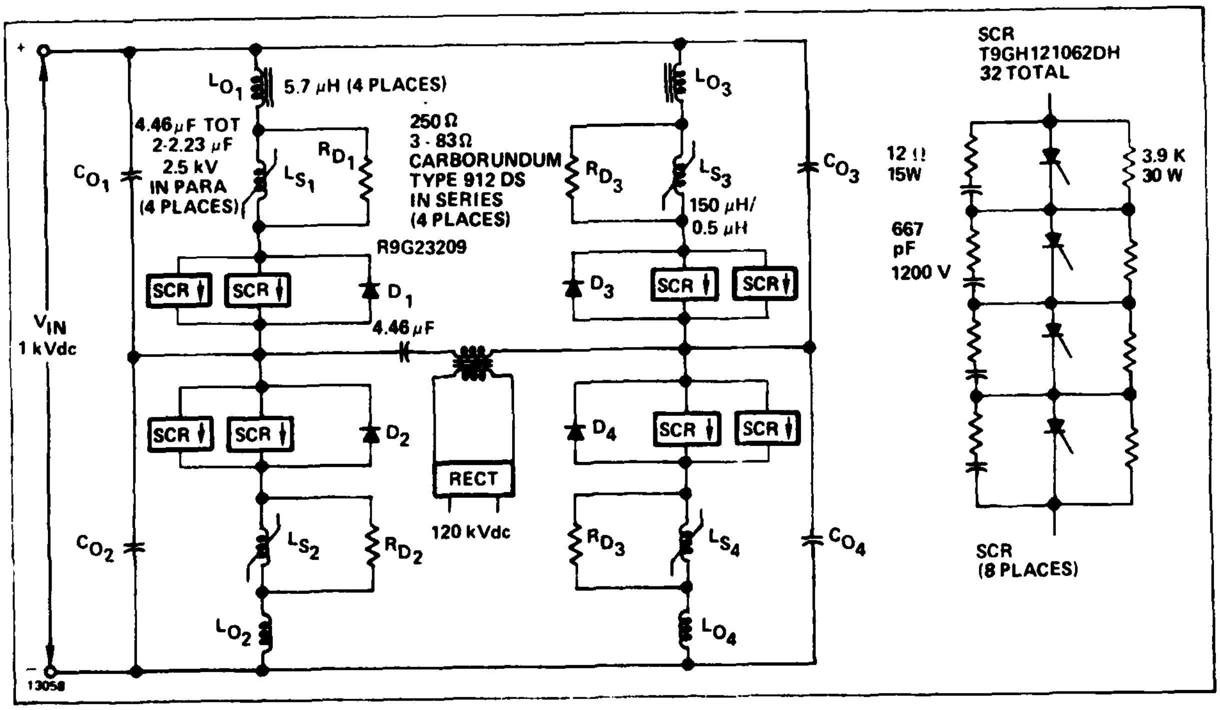

Figure 8 - Inverter Schematic For 0.5 MW, 1 kVdc In, 120 kVdc Out, 15 kHz Continuous Duty

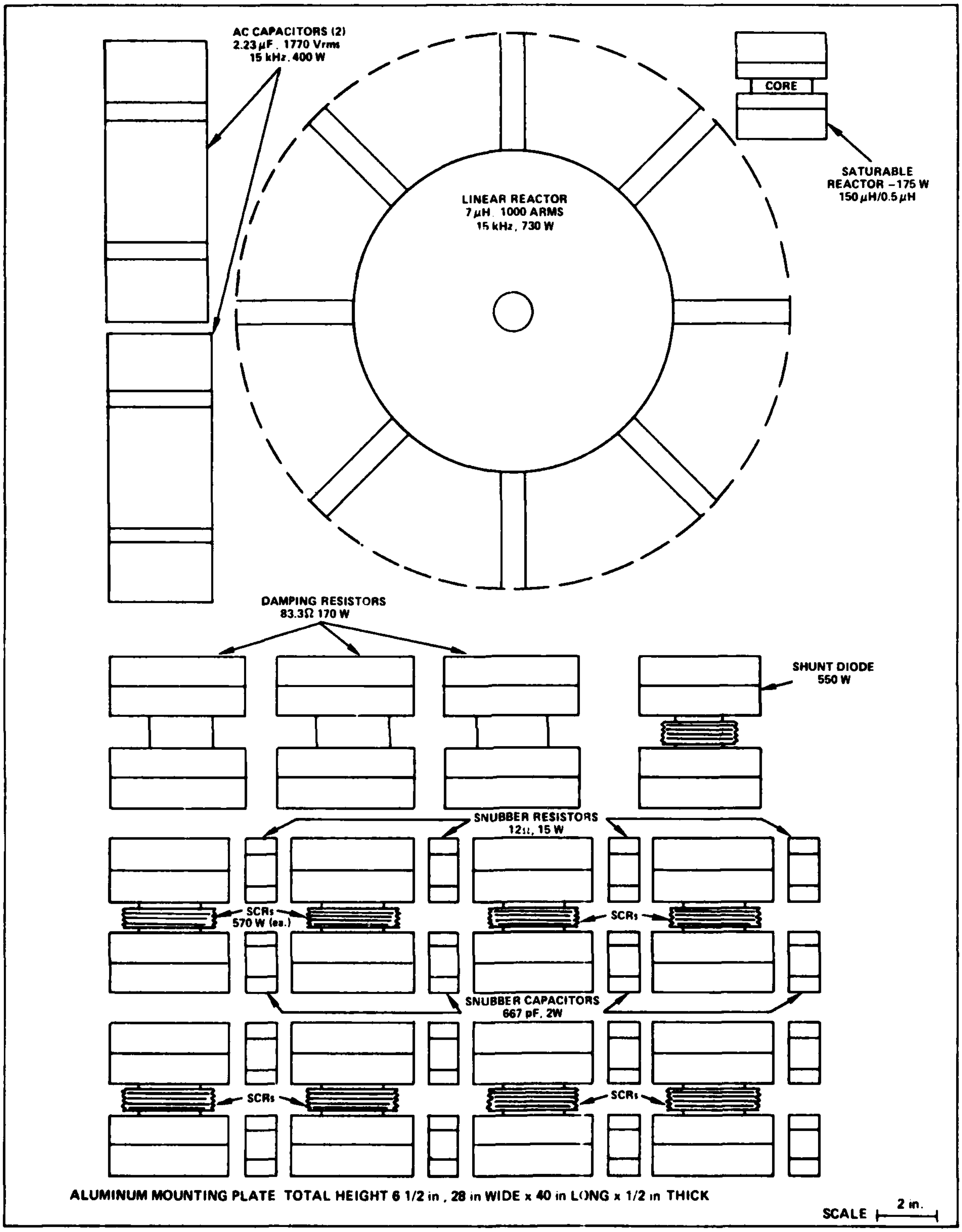

Figure 9 - Preliminary Layout Of 500 kW, 1000 V Input Inverter (One-Quarter Circuit)

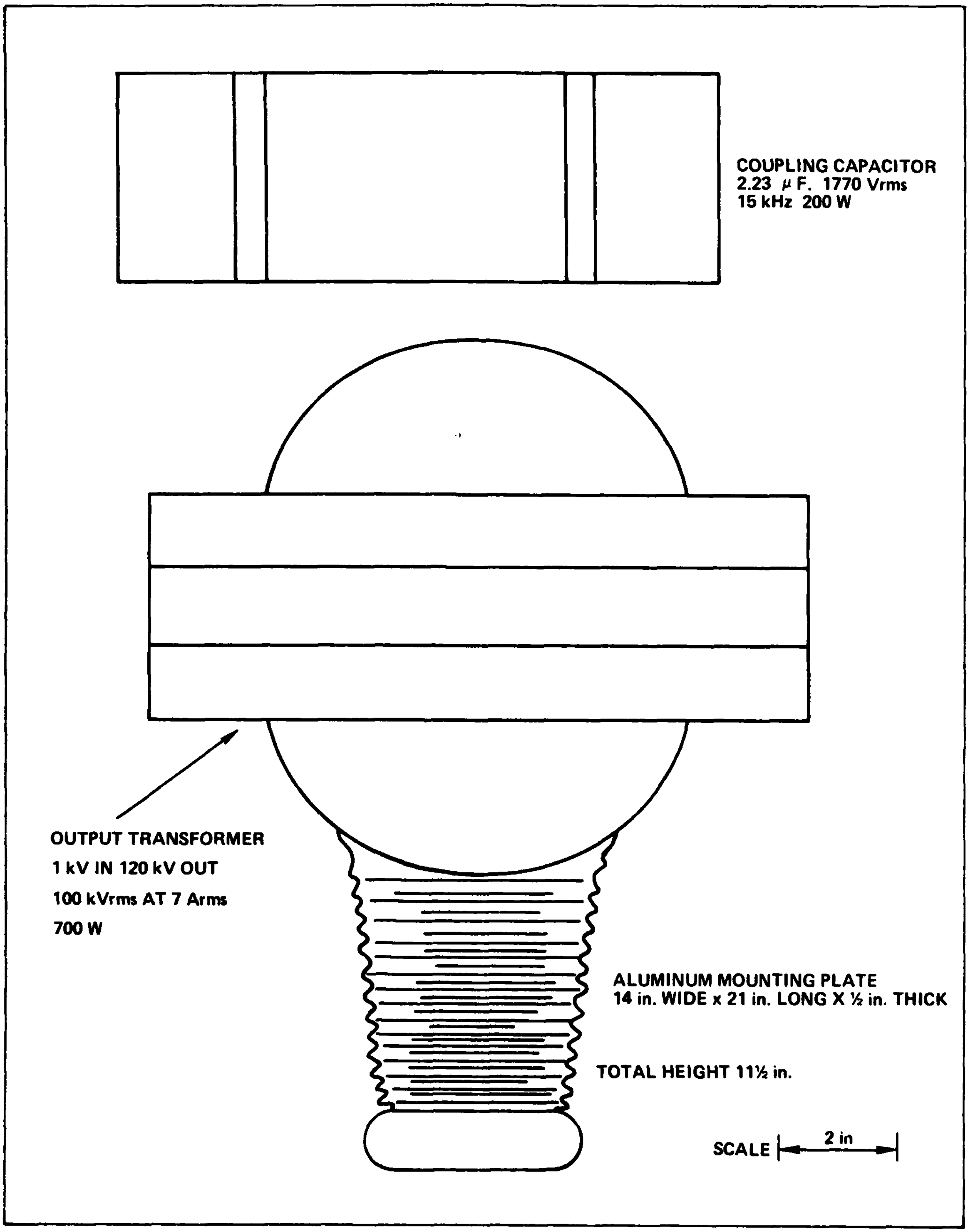

Figure 10 - Inverter Output Coupling Unit

b. **Design Techniques**

Reducing the output transformer heat loss for continuous operation resulted in 700 total watts of heat loss concentrated mainly in the core (80 percent or 560 W) where it could be simply conducted from the shell-type, two-core design. The exposed lamination edges are used for direct heat transfer from aluminum side plates to the spacecraft wall using thin 5 mil thickness CHO-THERM • insulation between them.

Each winding then has approximately 10 percent or 70 W heat loss. The primary winding is electrically at only 1770 Vrms, therefore a slitted aluminum winding tube 1/4-in. thick is used to conduct the copper loss out of the foil-wound coil with only a 25°C average winding temperature rise over ambient.

In the case of the high voltage secondary windings, also foil-wound, the winding copper loss is conducted from the foil to the BeO discs on each side through the epoxy encapsulation. Total secondary average winding temperature rise is 70°C over ambient.

Heat transfer from other components to the baseplate, such as the capacitors, disc resistors and linear reactors was accomplished through substantial aluminum mounting brackets clamped as shown for the saturable reactor in Figure 11.

c. **Spaceborne 250-kW Inverter**

In order to more nearly approximate the anticipated output of solar cell arrays it was necessary to consider the effect on the inverter design of reducing the operating parameters to 250 kW average power and 400 V output. Conversion frequency and output voltage would remain unchanged at 15 kHz and 120 kV, respectively.

The 250-kW inverter design alternative uses the same design approach and the same semiconductors as the 500-kW inverter. The number of SCRs and associated snubber resistors and capacitors are halved from 32 to 16 because the input voltage is reduced from 1000 V to 400 V. Similarly, the number of damping resistors has been reduced from 12 to four and their dissipation from 2000 to 400 W, for the same reasons.

Fundamentally, however, actual inverter circulating current is increased by 25 percent because the 50 percent reduction in output power is more than offset by the 60 percent reduction in input voltage. Consequently, the inverter capacitor values are increased 25 percent and the linear reactor inductance decreased by 25 percent.

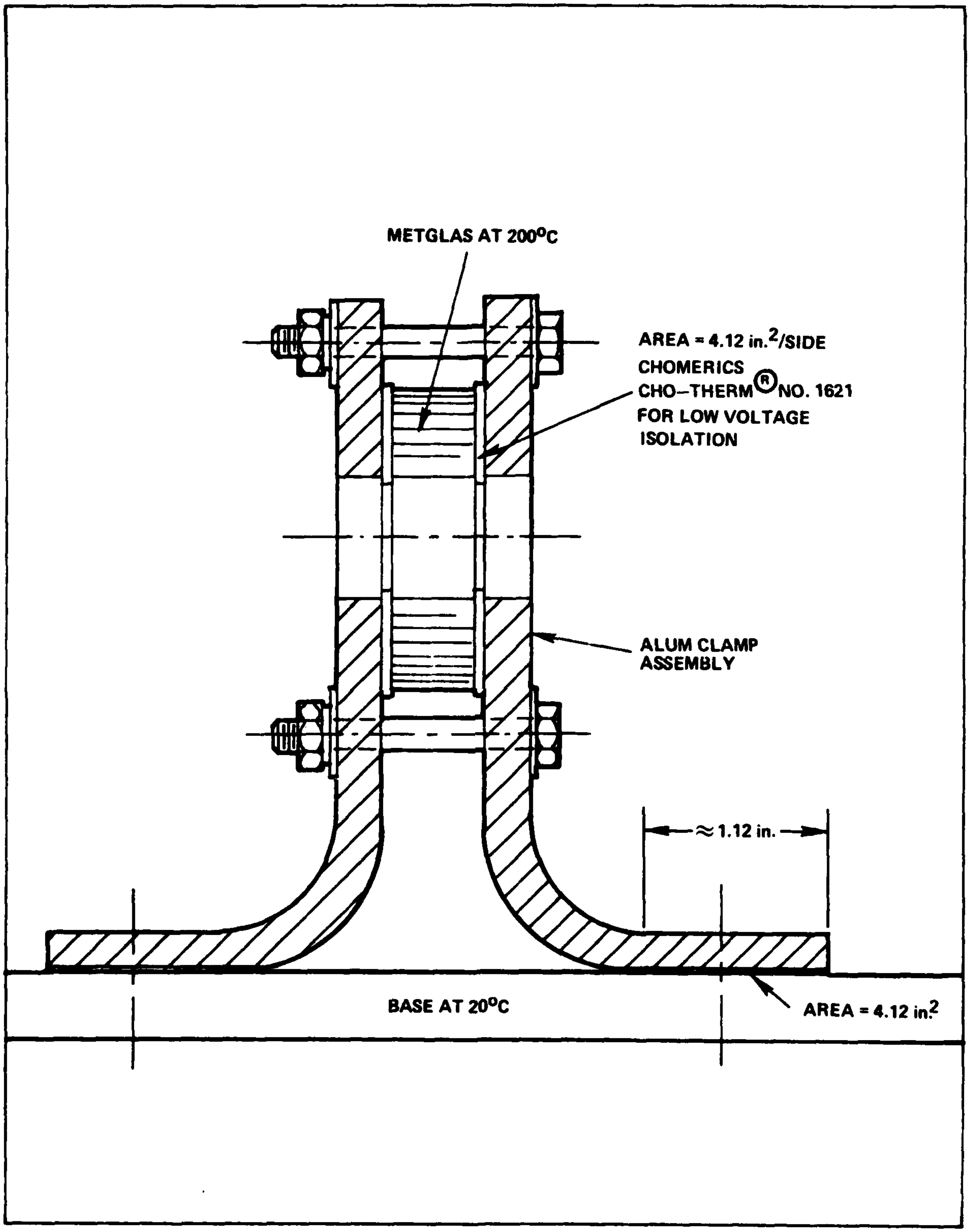

Figure 11 - Saturable Reactor Mounting Assembly

However, the linear reactor energy rating (1/2 LI^2) is actually increased 17 percent due to the increase in current. The number of resonating capacitors is reduced from eight to four, each rated 875A and 710 Vrms. Thus the size and losses associated with the remaining individual components used in the 250-kW inverter increase over those required for the 500-kW prototype design.

Efficiency is adversely impacted, dropping from 94 percent to 92 percent. However, actual losses drop from 30 kW to 22 kW allowing a 27 percent reduction in external space radiator area. Nevertheless, the result is consistent with expected efficiency from a 250-kW inverter operating at 1000 V input.

Despite the 50 percent reduction in output power, the output coupling unit is reduced in weight only from 187 lb to 142 lb (24 percent) and in volume from 1.96 ft^3 to 1.64 ft^3 (16 percent). The reason is that the output voltage of 120 kV in both cases results in the difficult problem of electrically insulating the high voltage winding while conducting the copper losses out of it.

Size and weight for the inverter sections are reduced from 16.9 ft^3 to 11.8 ft^3 (30 percent) and from 916 lb to 700 lb (24 percent) a substantial savings in each category. The main contributor to the weight of this inverter is the linear reactor (44%), followed by the mounting plates (15%), output transformer (14%) and SCR assemblies (11%). The remaining 16% of the weight is made up of miscellaneous small components and hardware.

Total inverter size and weight are reduced from 18.8 ft^3 to 13.4 ft^3 (29 percent) and from 1103 lb to 842 lb (24 percent). The weights include mounting the components to a half-inch-thick aluminum plate along with the necessary controls and hardware. A preliminary layout is shown in Figure 12. A 20°C wall temperature would require a radiating area of 620 ft^2.

Summarizing the comparison between the two inverters, the reduction in input voltage is favorable and consistent with semiconductor capabilities as low voltage, high current devices, relatively speaking. The dissipation density is increased on an inverter section assembly basis from 6.5 W per $in.^2$ to 6.7 W per $in.^2$ on the mounting plate, only a three percent increase. Major components, such as SCRs and the shunt diode have had an individual 33 percent increase in heat loss, requiring a similar increase in their heat sinks.

Overall, the 250-kW inverter is as practical at 400 V input as at 1000 V input with proper attention to current conductors and connections and particularly heat sinking of the components.

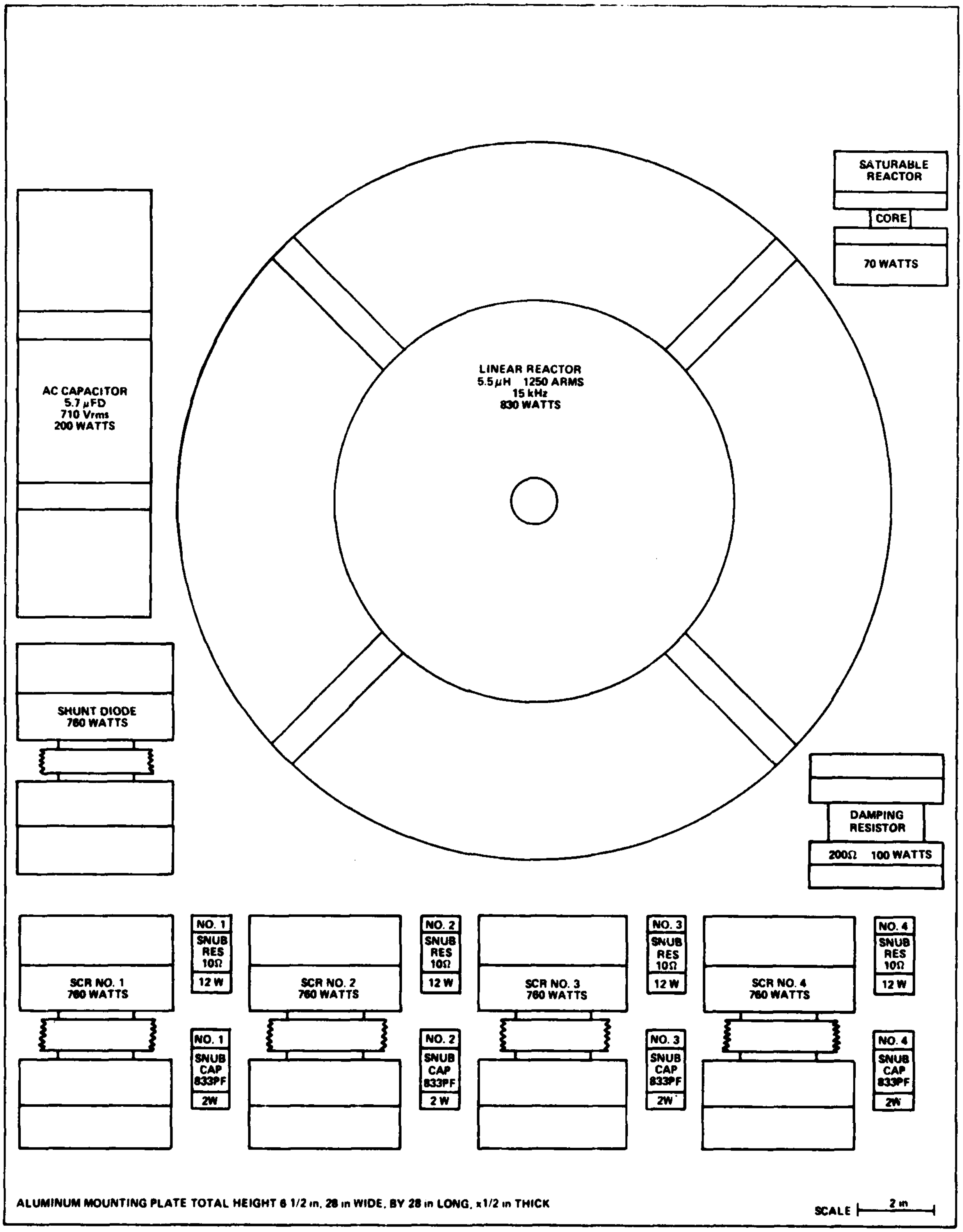

Figure 12 - Preliminary Layout Of 250 kW, 400 V Input Inverter (One-Quarter Circuit)

SECTION IV
CONCLUSIONS

During the three phases of this study, four types of power conditioning subsystems were examined and point designs were prepared for a broad range of operating parameters. The environmental conditions, both airborne (Phases I and II) and spaceborne (Phase III) were somewhat idealized for simplicity. Nonetheless, significant comparisons could be made between the sizes and weights of the various subsystem design points.

A comparison of the Phase III results with those in Phase II for similar parameter values, illustrated in Table 6, demonstrates the distinct advantage of burst mode operation over continuous operation where size and weight must be minimized.

In general, the limitations found in attaining subsystems of reduced size and weight were attributed to the lack of components, especially SCRs and diodes, capable of operating reliably and efficiently at the high voltages, currents and conversion frequencies under study. The present status of magnetic components and pulse capacitors also appeared as limits to further progress in subsystem size reduction.

Packaging of individual semiconductor elements could be improved and optimized with respect to the parameters under study in this program.

TABLE 6

AIRBORNE AND SPACEBORNE POWER CONDITIONING SUBSYSTEMS

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Subsystem	Average Power (MW)	Frequency (kHz)	Output (kV)	Airborne (lb)	Airborne (ft^3)	Spaceborne (lb)	Spaceborne (ft^3)
Three-Phase Rectifier	21 7	0.6 1.8	100 1	3280 (a) 405 (a)	196 16	3334 (a) 534 (a)	196 16
Inverter-Fed Rectifier	0.5	20	80	153 (a)	10	1035 (b)	22
Inverter (1 kV input)	0.5	15	120	585 (a)	16	1103 (b,c)	19

Notes: (a) Intermittent Duty, 2 min bursts
(b) Continuous Duty
(c) Efficiency increased to 94 percent from airborne design's 90 percent

SECTION V
RECOMMENDATIONS

Whether airborne or spaceborne, it was concluded in the previous section that further reduction in size and weight of high power subsystems is limited by the present state-of-the-art of semiconductor devices. Significant further development of such devices along these lines is very unlikely in a practical sense unless and until a market potential can be identified to justify the expense of development. It is therefore recommended that a hybrid approach be examined in which both solid-state and advanced switch tube devices would be used to accommodate the needs of high power subsystems.

With respect to space applications, it is clear that more detailed work on subsystem packaging and thermal management is necessary to optimize the spaceborne designs. A more realistic environment which includes launch conditions and hostile radiations, both natural and man-made, must be considered. Reliability requirements and maintenance intervals should be evaluated with consideration of the opportunities for more frequent maintenance afforded by space shuttle availability. Relaxation of these requirements will allow the utilization of components more suitable for compact high power, high voltage power conditioning subsystems which have not previously been considered, such as switch tubes.

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(1) "Power Conditioning Subsystem Design", Interim Report for Period 17 September 1979 - 30 November 1981, Report No. AFWAL-TR-82-2005 (January 1982).

(2) "CHO-THERM R Elastomers for Efficient Heat Transfer and Electrical Isolation", Technical Bulletin 41, Chomerics, INc., Woburn, Massachusetts.

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